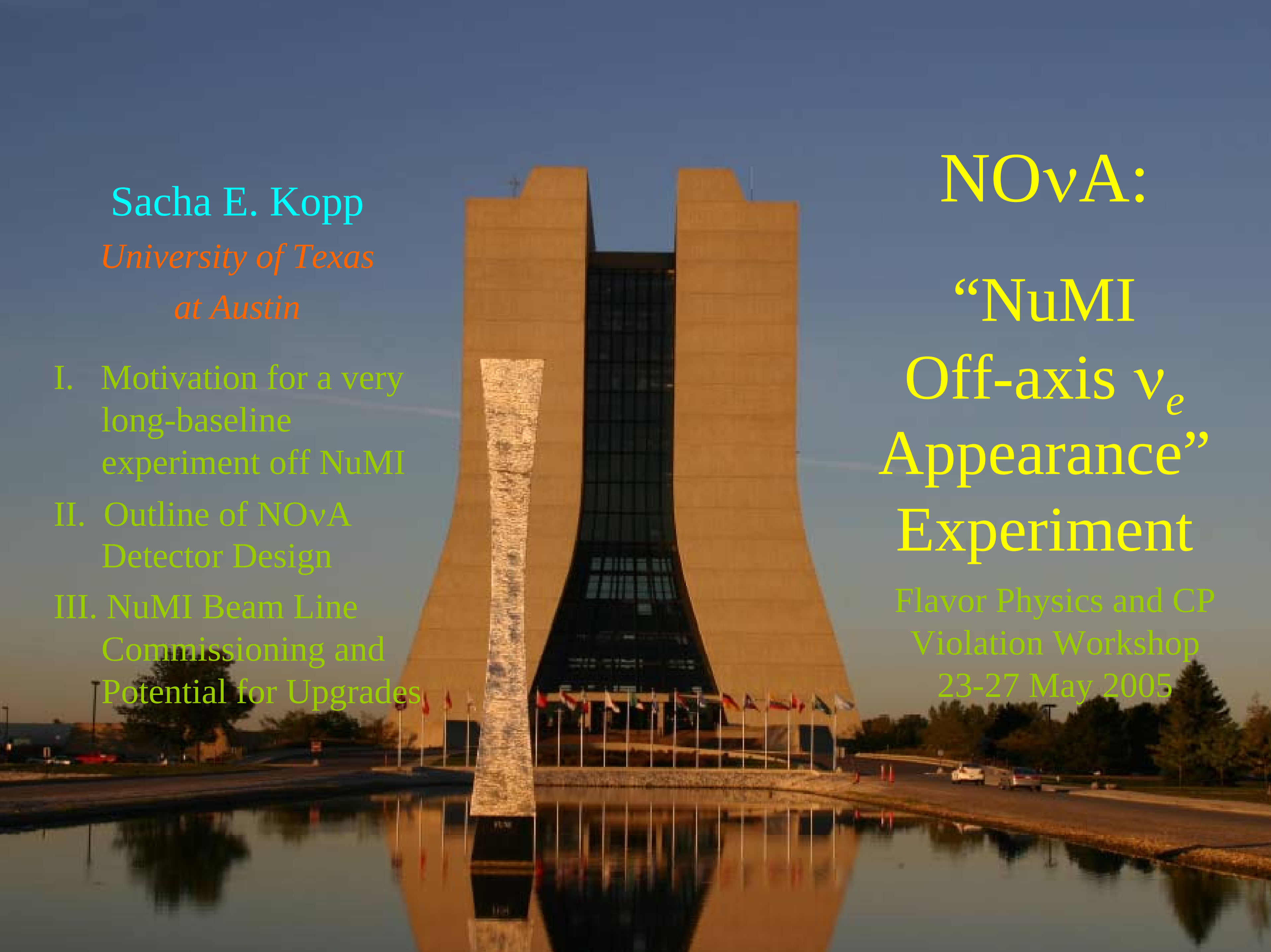


NOνA: “NuMI Off-axis ν_e Appearance” Experiment

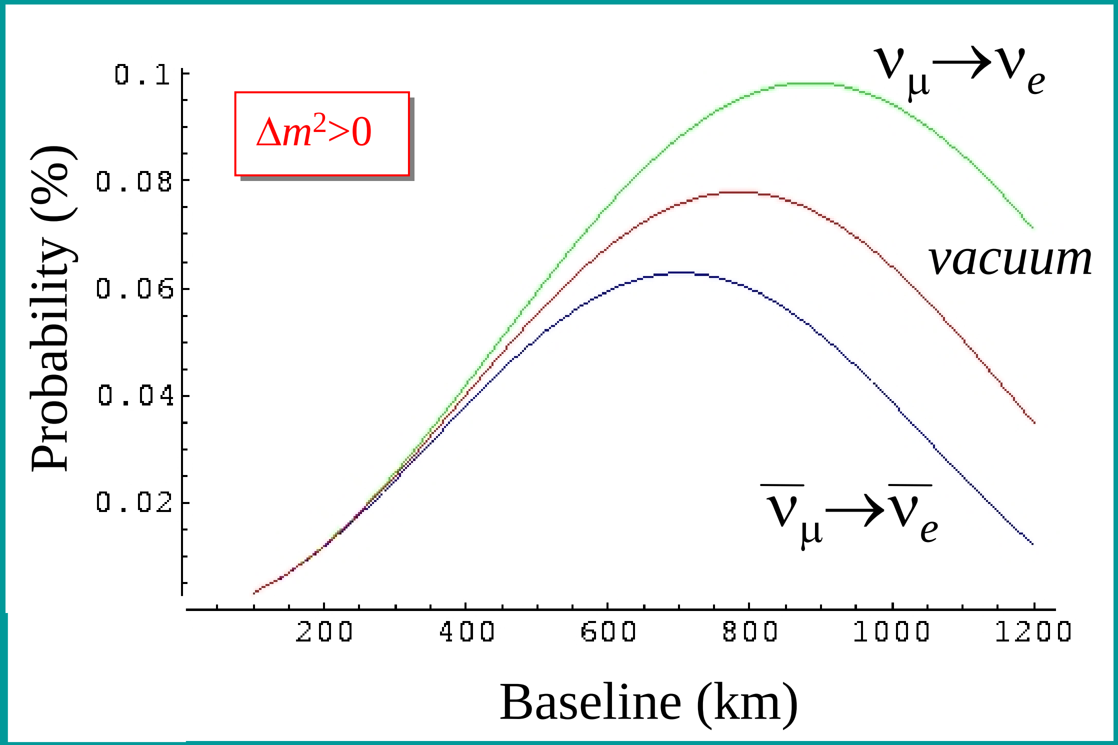
Sacha E. Kopp

University of Texas at Austin

I. Motivation for a very long-baseline experiment off NuMI
II. Outline of NOνA Detector Design
III. NuMI Beam Line Commissioning and Potential for Upgrades

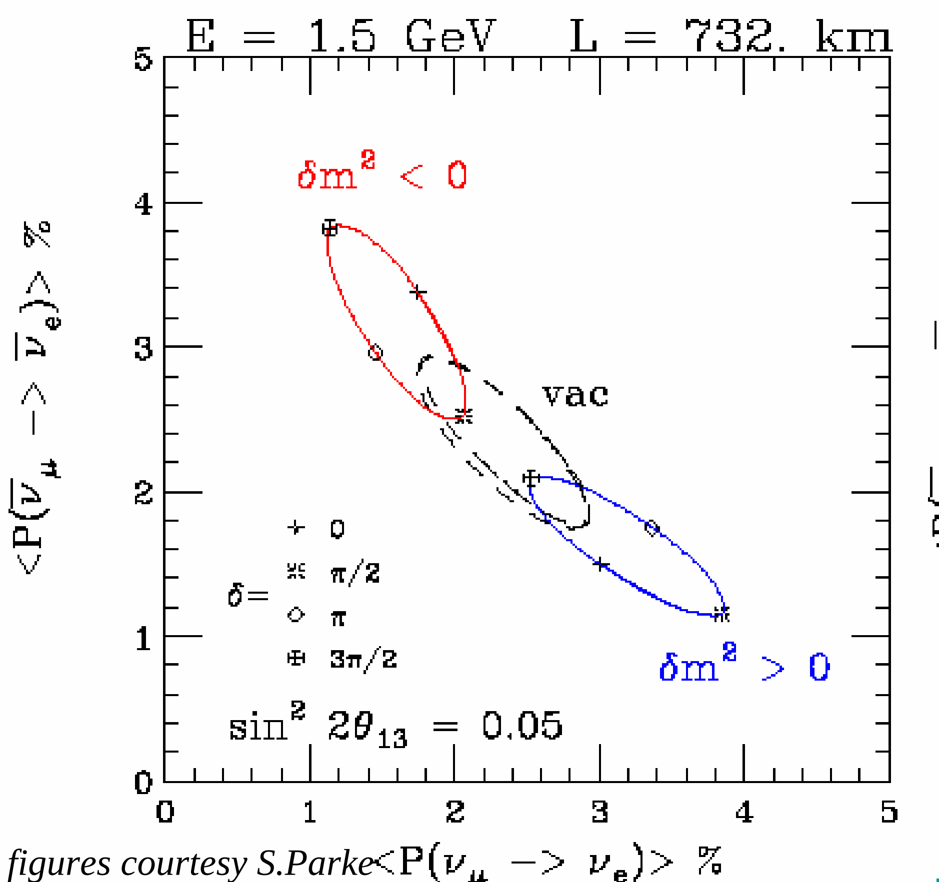
Flavor Physics and CP Violation Workshop
23-27 May 2005

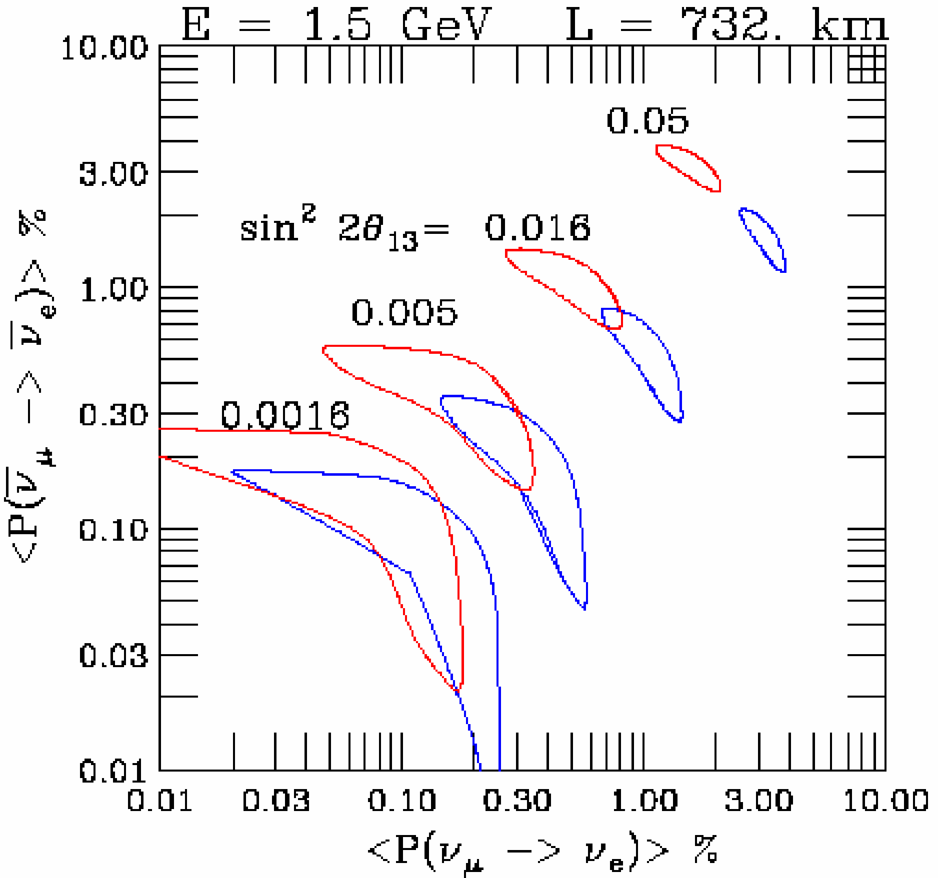
Why Build a Very Long-baseline ν_e Appearance Experiment?



- Rate difference $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ due to…
  - CP violation: $\Delta P_\delta(\nu_\mu \rightarrow \nu_e) \sim \frac{1}{2} \cos\delta\, J_r\, \Delta_{\mathrm{solar}} \sin 2\Delta_{atm} \pm \sin\delta\, J_r\, \Delta_{\mathrm{solar}} \sin^2\Delta_{atm}$
  - Matter effects: $P_{\mathrm{matt}}(\nu_\mu \rightarrow \nu_e) \sim \{1 \pm (2E/E_R)\}\, P_{\mathrm{vac}}(\nu_\mu \rightarrow \nu_e)$

Learning the Mass Heirarchy

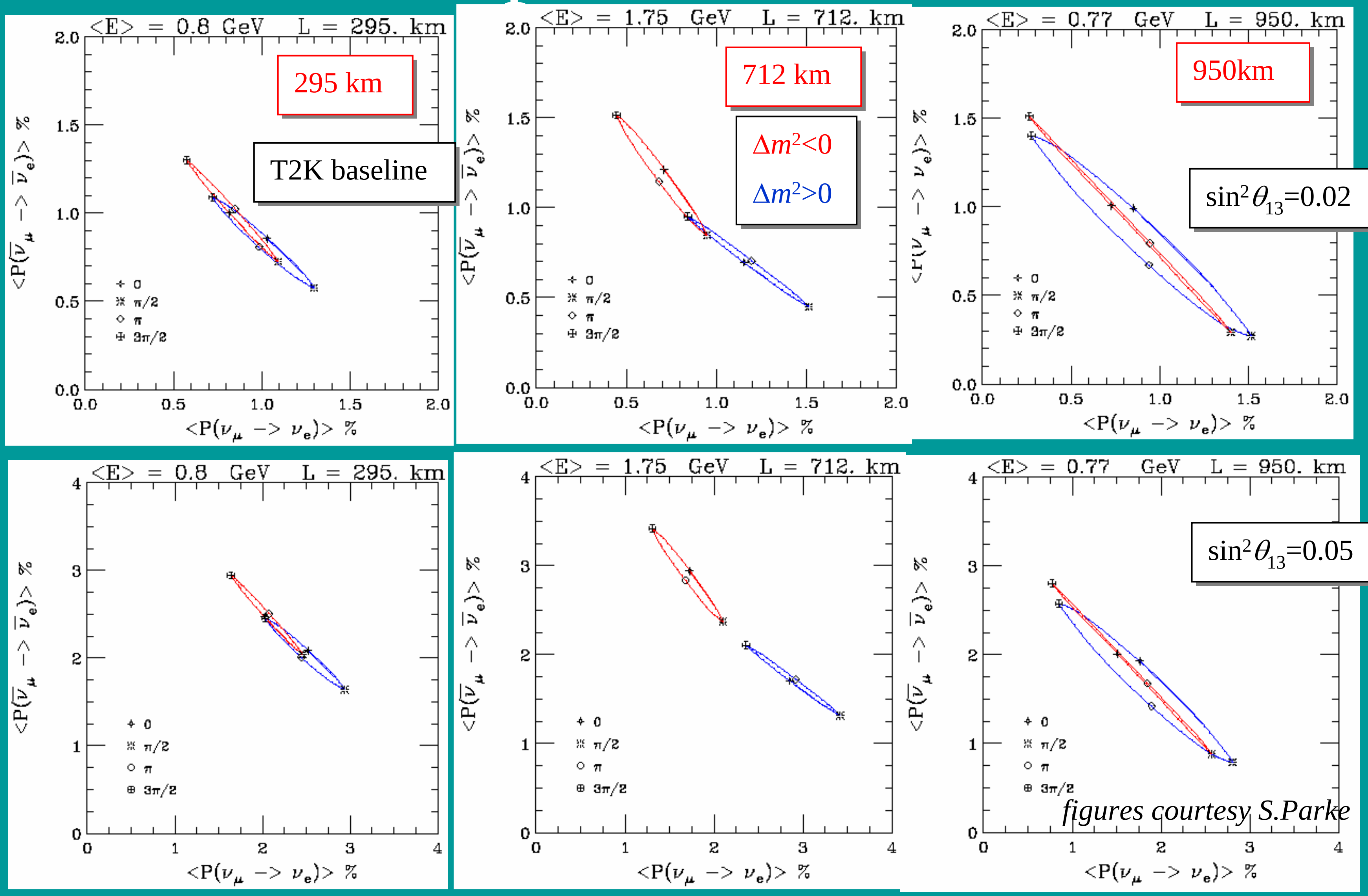




figures courtesy S.Parke

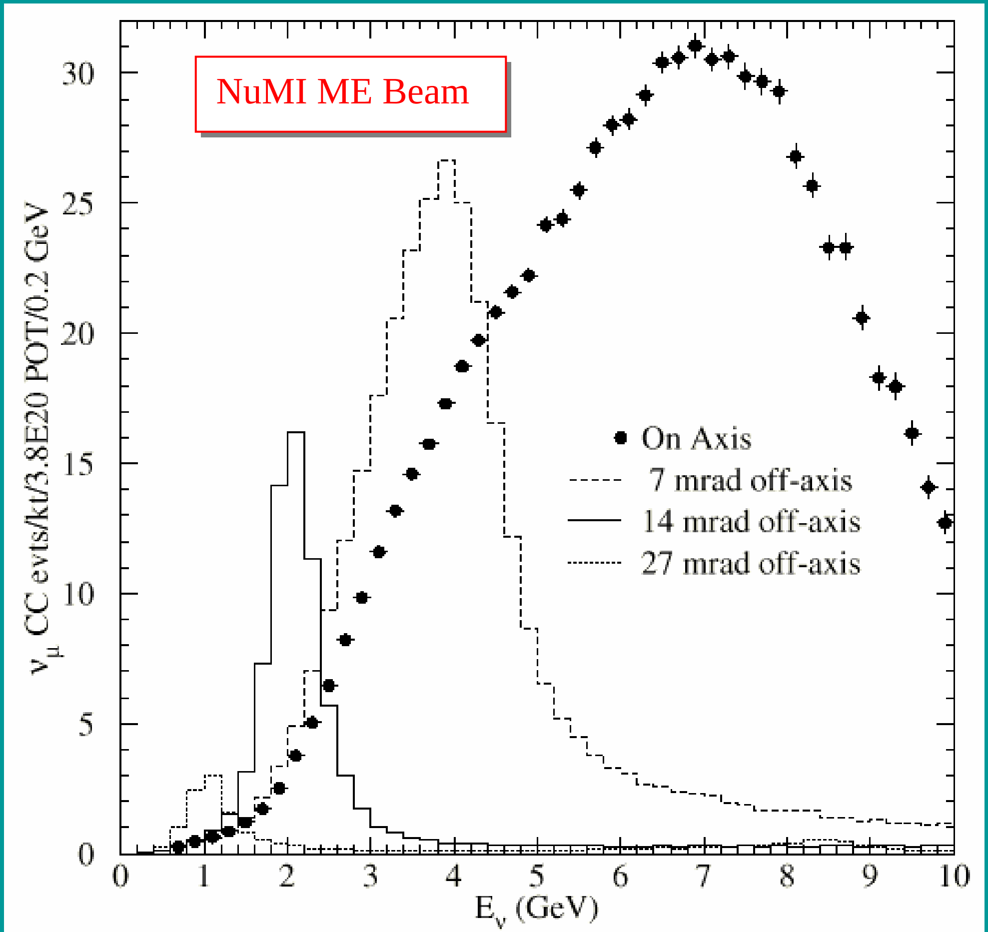
- Can we disentangle mass heirarchy and CP violation?

Compare Baselines



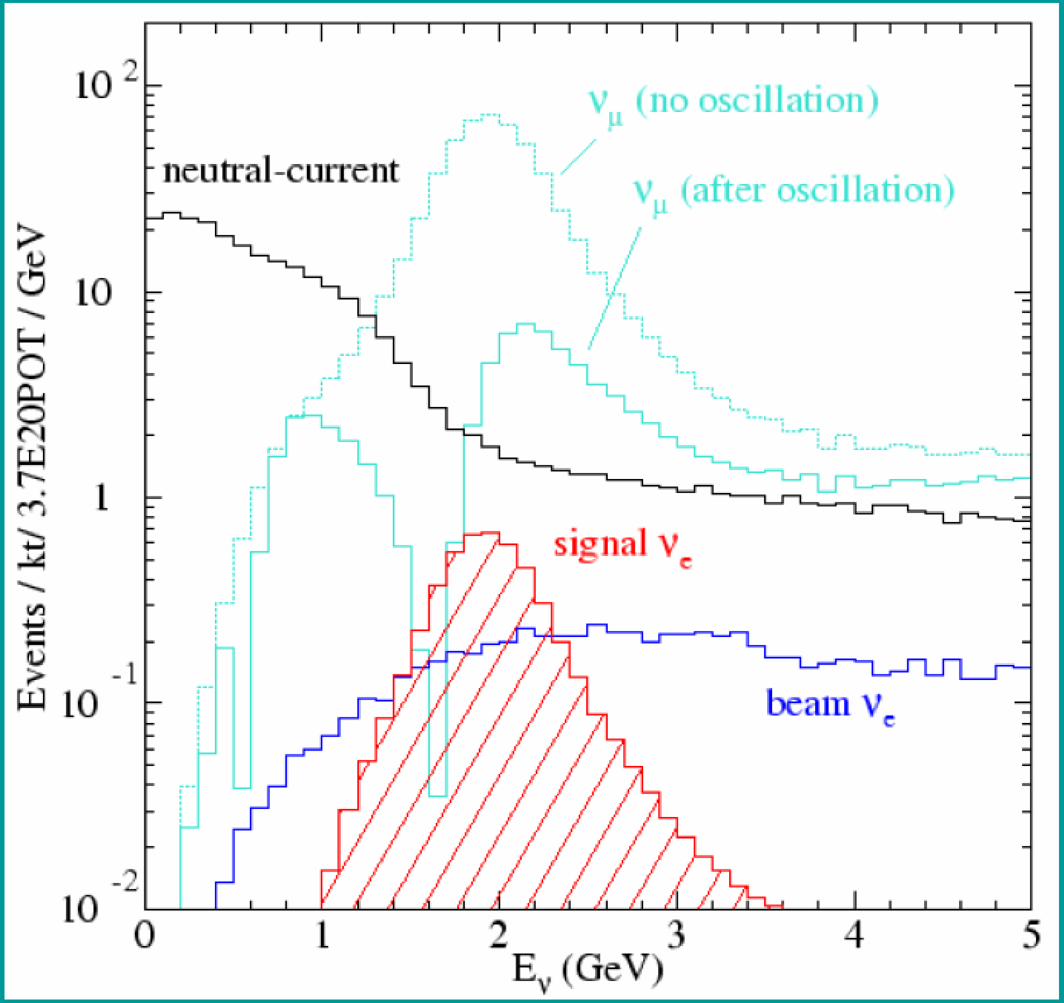
Off-Axis Beam from NuMI

- Plots assume current neutrino target, horns, L=735 km
- Note that 3.8×10^{20} POT is 1.5years of NuMI beam without upgrades
- Neutrino event rate at far detector gets boost because higher E_ν
- Variable energy beam design (M.Kostin *et al* NuMI-B-783) can help move peaks dynamically
- If antineutrino running is undertaken, event rate will take factor 3 hit in because of xsec's.



ν_e Backgrounds Summary

- Plot assumes $|U_{e3}|^2=0.01$, $\Delta m^2=3.0\times10^{-3}$ eV^2.
- NC is all interactions before any identification cuts.
- Detector design requires >10× reduction in NC events



Comparison of Exp'ts

(*a very old comparison from 2002 LOI*)

NuMI-MINOS,
2 yrs @ 8E20 POT

signal	beam ν_e	ν_μ CC	$\nu_\mu \to \nu_\tau$	NC< 10 GeV	NC > 10 GeV
8.5	5.6	3.9	3.0	15.7	11.5

NuMI Off-Axis,
5yrs @ 4E20 POT/yr
712 km baseline

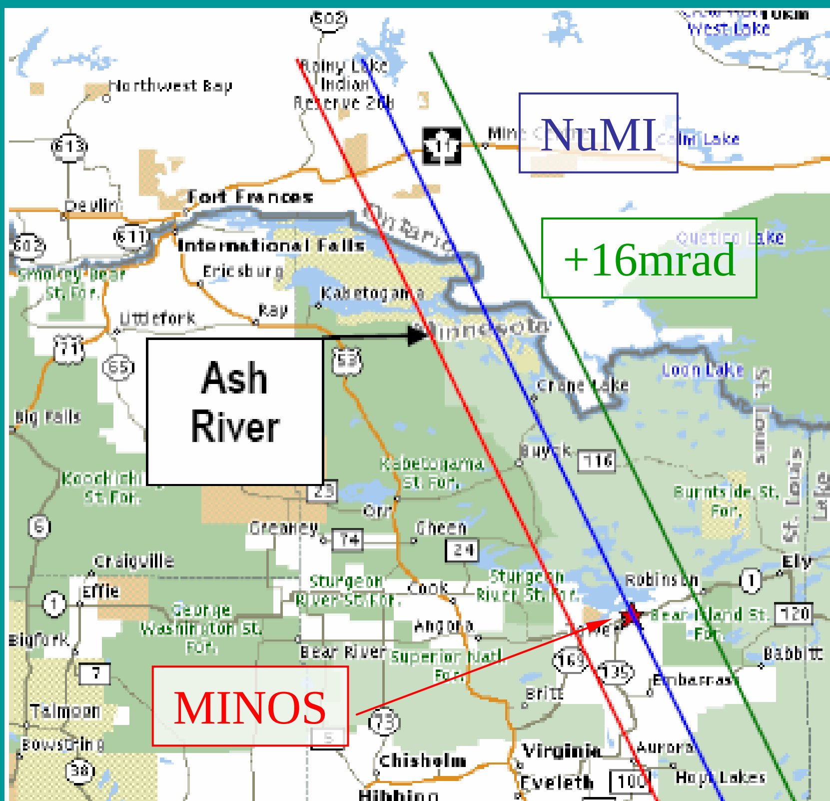
	ν_μ CC	NC	Beam ν_e	Signal ν_e
all	10714	4080	292	302
after cuts	1.8	9.3	11	123

JHF Phase I,
5yrs @ 0.77MW
295 km baseline

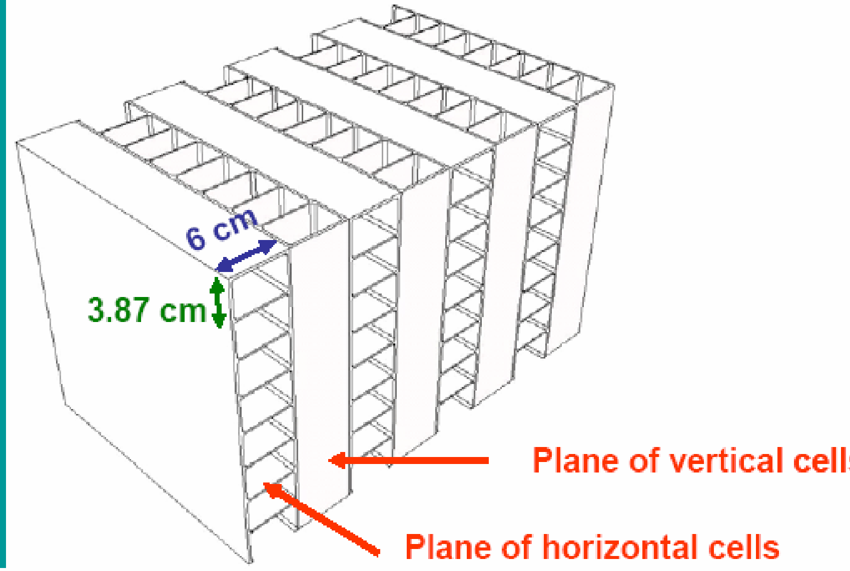
	ν_μ CC	NC	Beam ν_e	Signal ν_e
all	12104	5696	295.4	293
after cuts		10.2	10.2	85.5

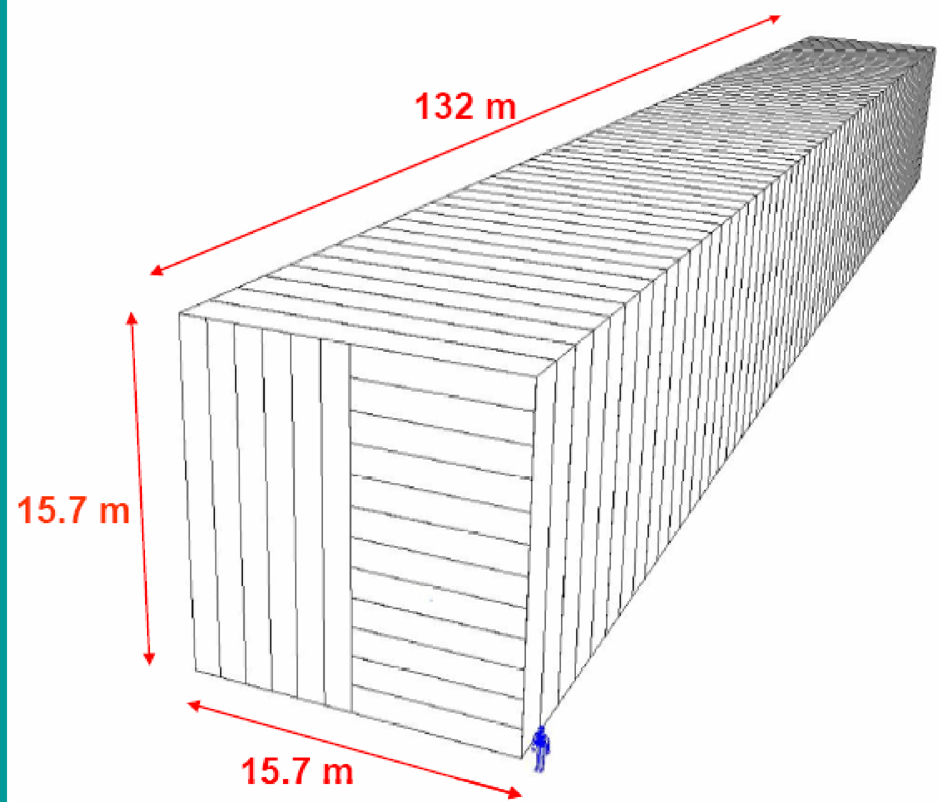
- Assume $\Delta m^2 = 3.0 \times 10^{-3}$ eV^2, $\sin^2\theta_{13}$=0.1,
- For NuMI, the 2002 LOI assumed a 20kt detector, 85% fid.vol, analysis of low-*Z* calorimeter. New P929 proposal calls for 30kton totally active detector
- Key point: even in absence of FNAL proton source improvements, NuMI can make up for lower proton power, longer baseline because of higher neutrino cross section, higher pion focusing yield at 120 GeV.

Totally Active Scintillator Detector



- 30 kton of PVC extrusions filled with liquid scintillator.
- *X*-*Y* tracking calorimeter ("totally" active, no absorber plates)

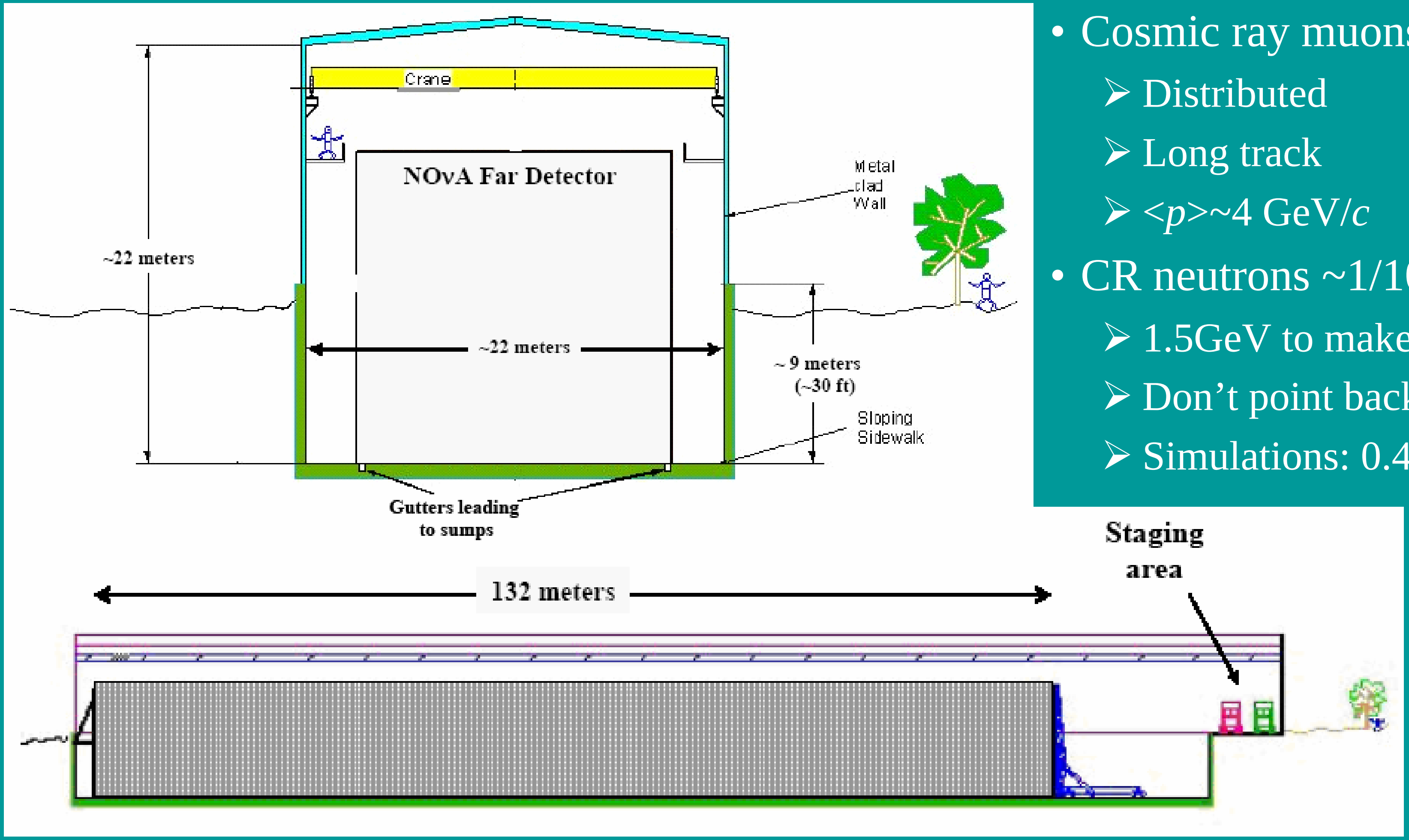




S. Kopp, FCP05 5/24/05

Detector Located on Surface

- Cost savings if we can skip overburden

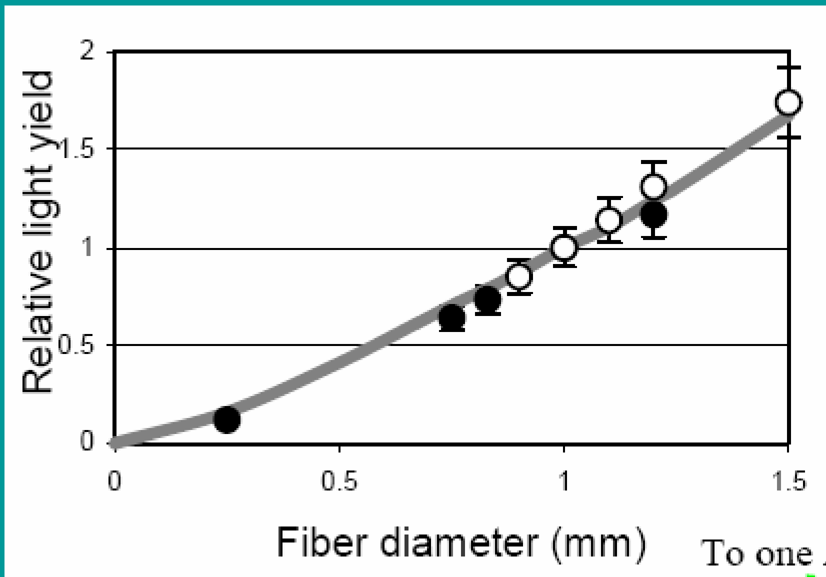


- Cosmic ray muons ~8/spill
  - Distributed
  - Long track
  - <*p*>~4 GeV/*c*
- CR neutrons ~1/100 spills
  - 1.5GeV to make a single π
  - Don't point back to FNAL
  - Simulations: 0.4evts / 5 yrs.

Light Collection

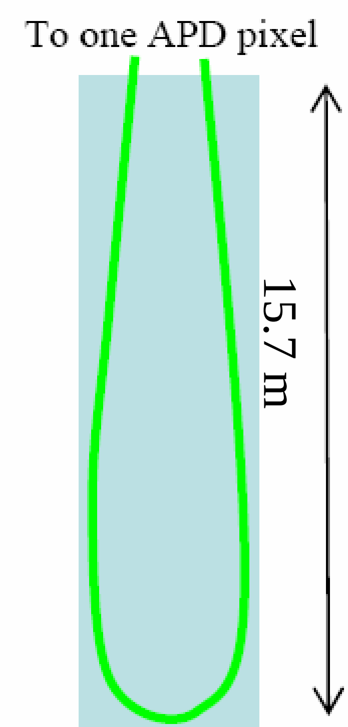
Expect 25pe/MIP in NOνA Detector at furthest light propagation length, based on scaling for the following:

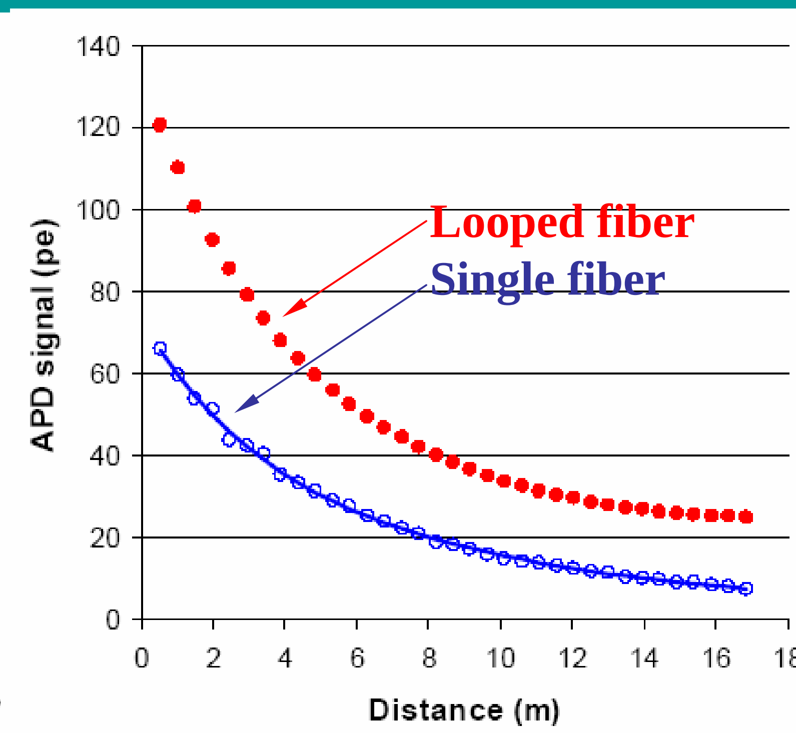
- Fiber diameter
- Liquid scintillator cell sizes
- Substitute APD's for PMT's
- Fibers in 'U' shape ⇒×2.
- Improved reflectivity of TiO_2 doped PVC



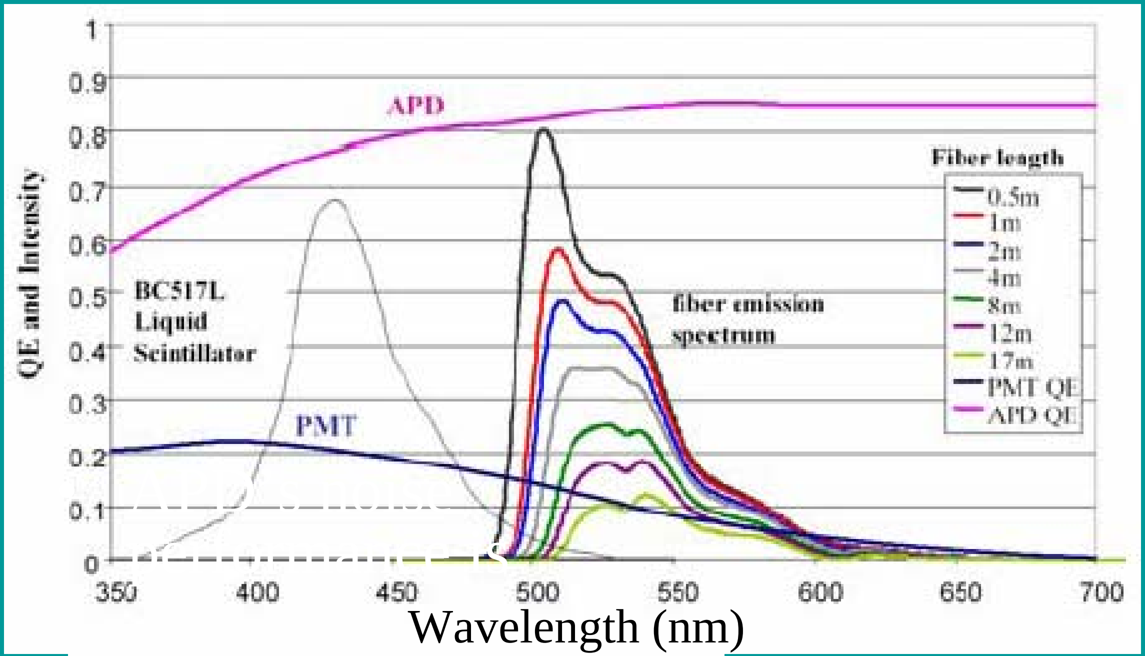
Two data points (not the same geometry as NOvA cell, but are the basis for scaling up light yields)

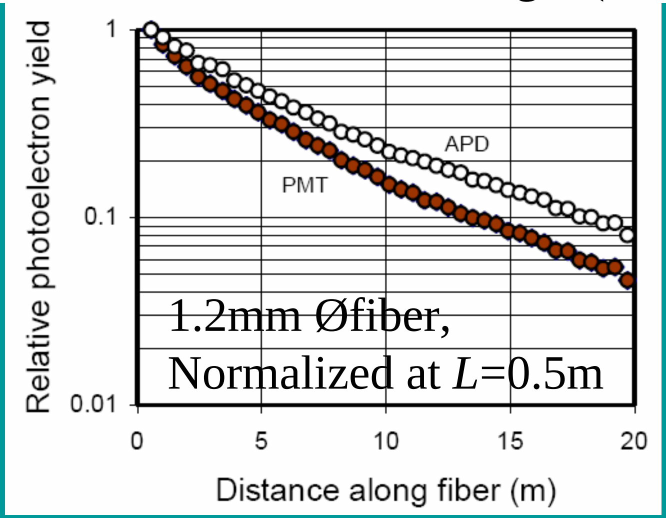
- MINOS has 0.95pe/MIP
- Cosmic ray test performed for NOvA showed 13pe/MIP



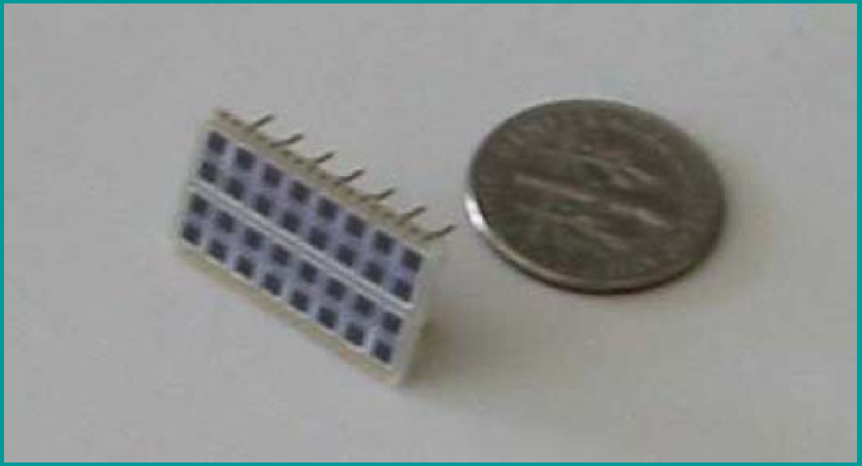


APD is Photosensor Choice

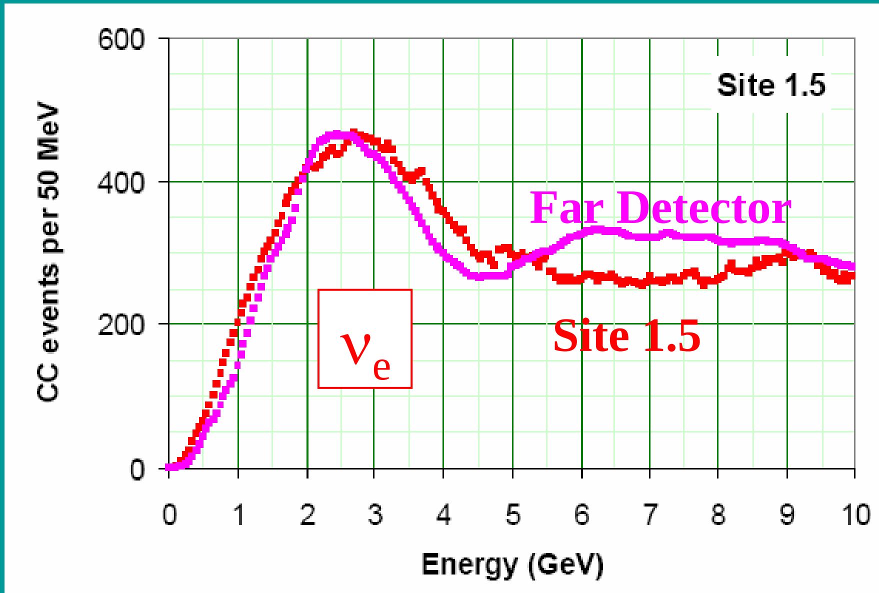


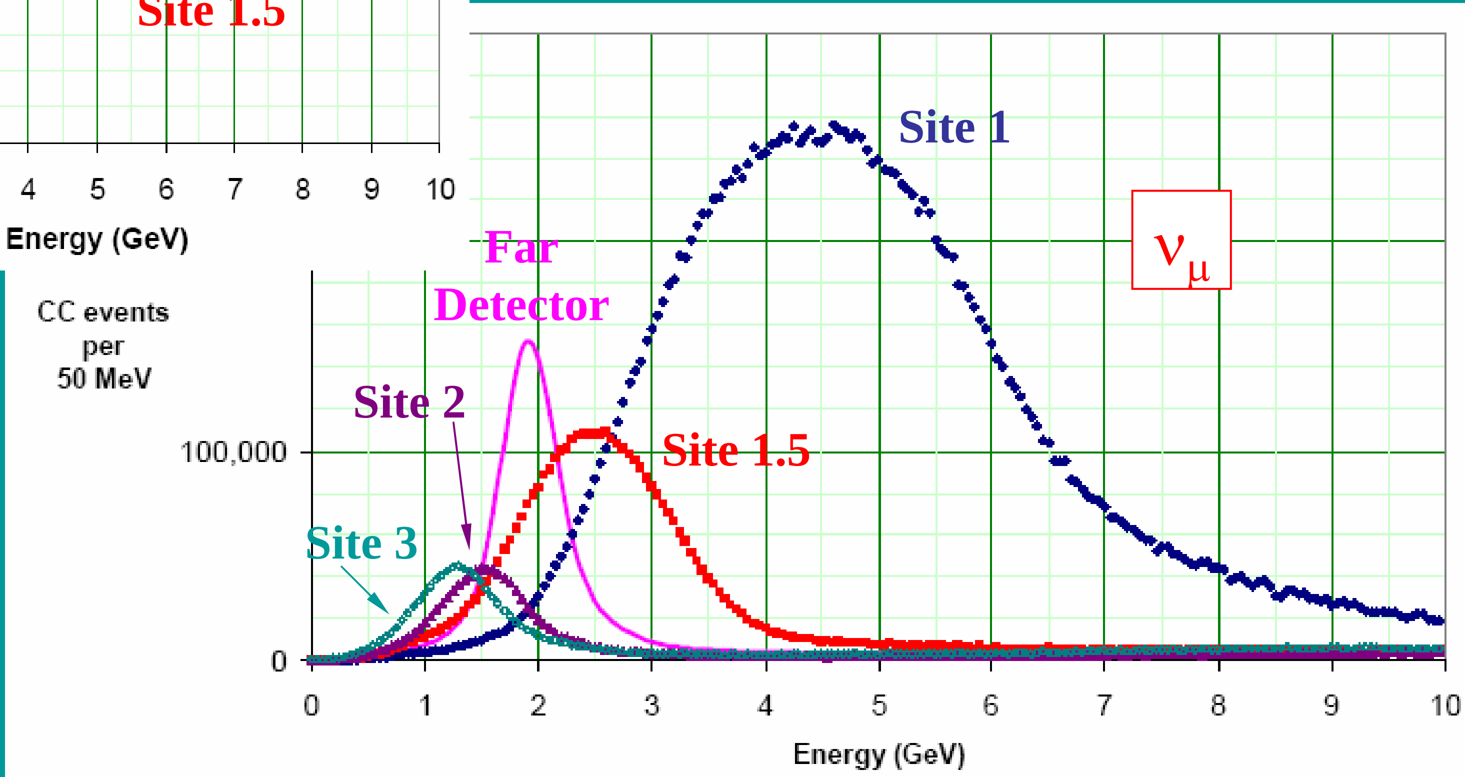


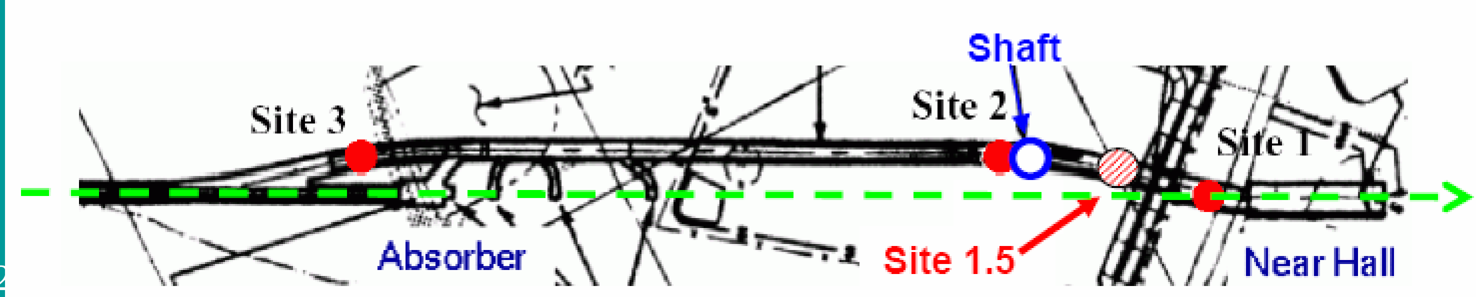
- APD's have flat response vs wavelength
- Of particular value since low wavelength fiber emission is attenuated for longest (16m) distances.
- Anticipate gain ~100, noise equivalent ~2pe when coupled to custom chip in process now (compare to 25pe/MIP)



Near Detector

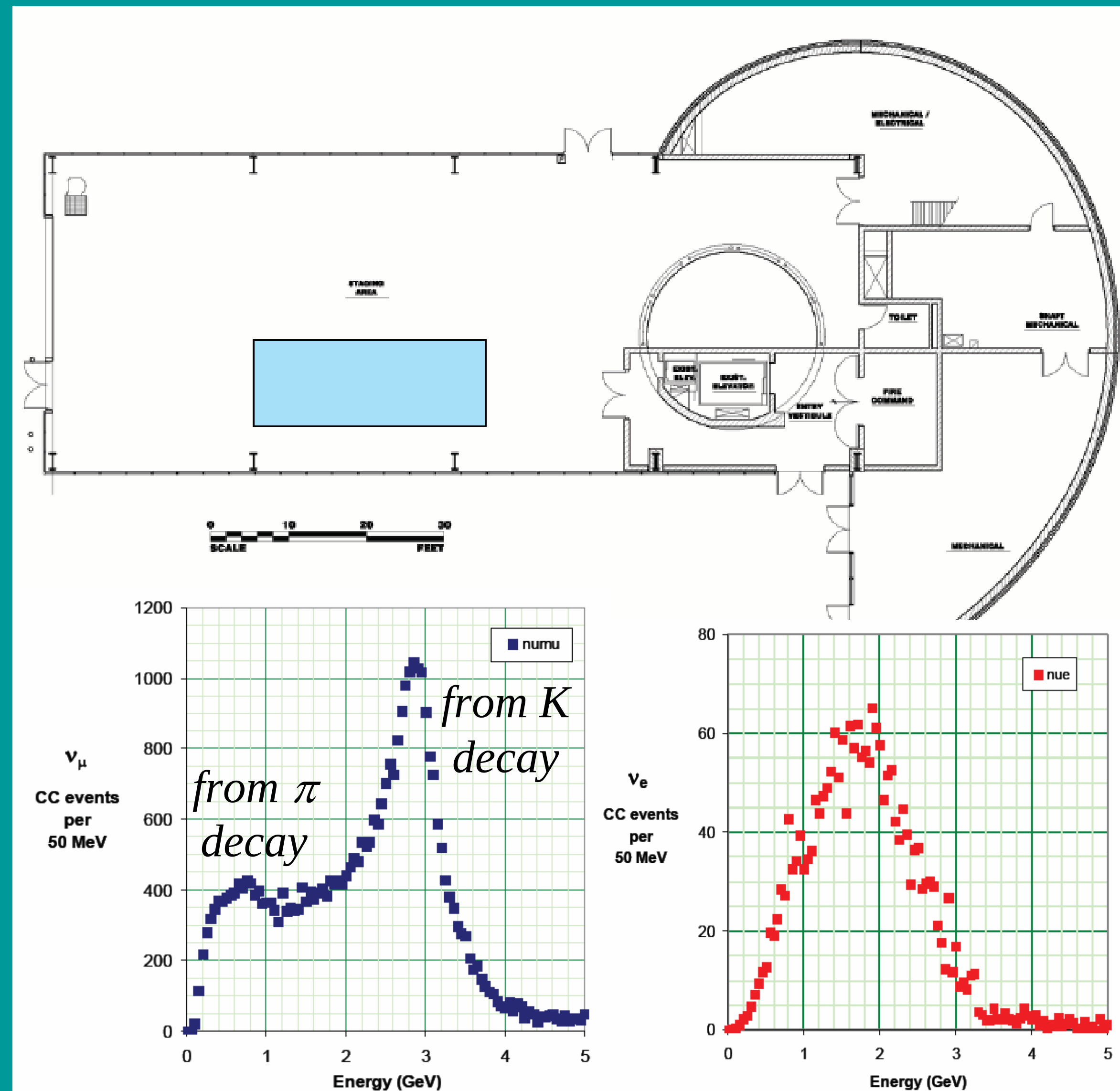






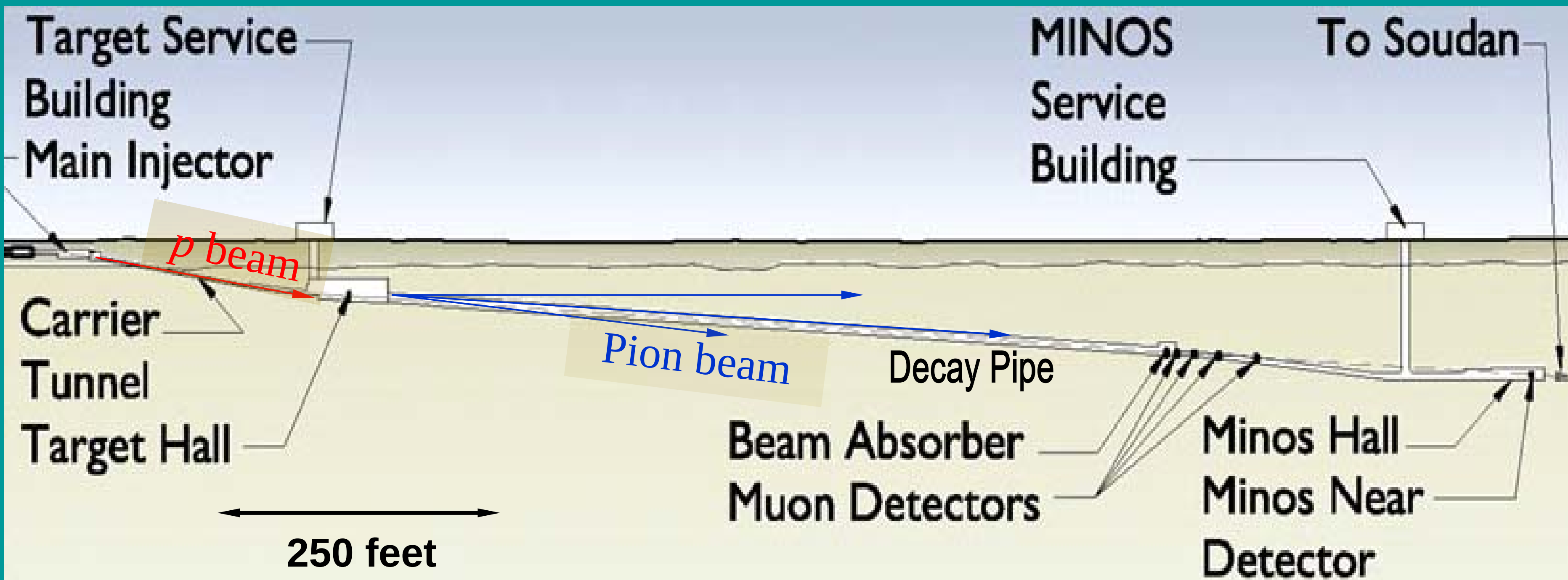
An Initial Beam Test

- As part of R&D effort, locate a 262 ton prototype detector in MINOS service building
- ~75mrad off-axis, 1km from NuMI target.
- Background from beam ν_e peaks in roughly correct location.
- Opportunity to operate a detector on the surface (similar to NOνA), without underground issues.
- Spectra shown are for 6.5×10^{20} POT
- NB: Already MiniBooNE observes NuMI neutrinos!



The NuMI Beam

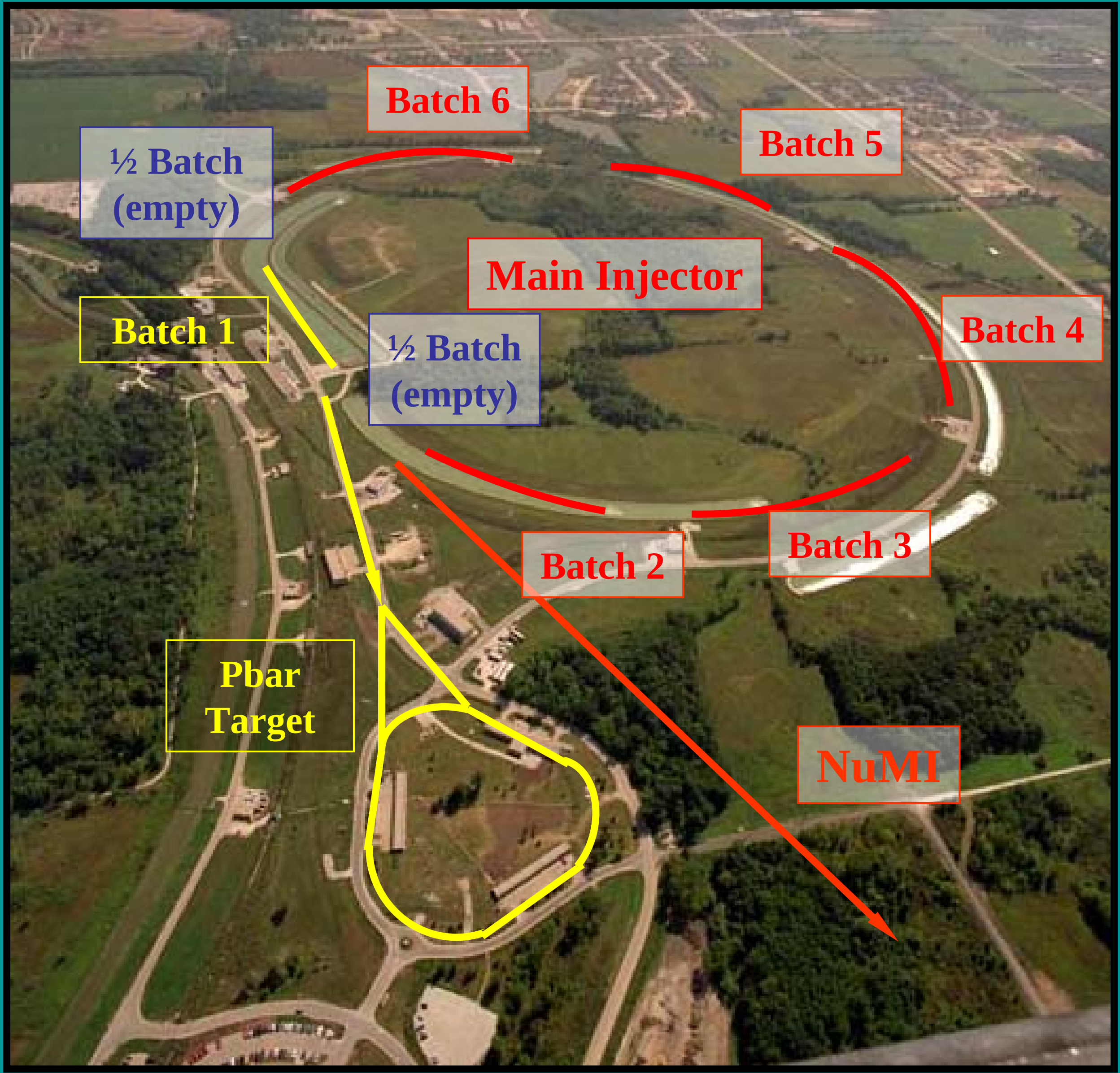
"Neutrinos at the Main Injector"



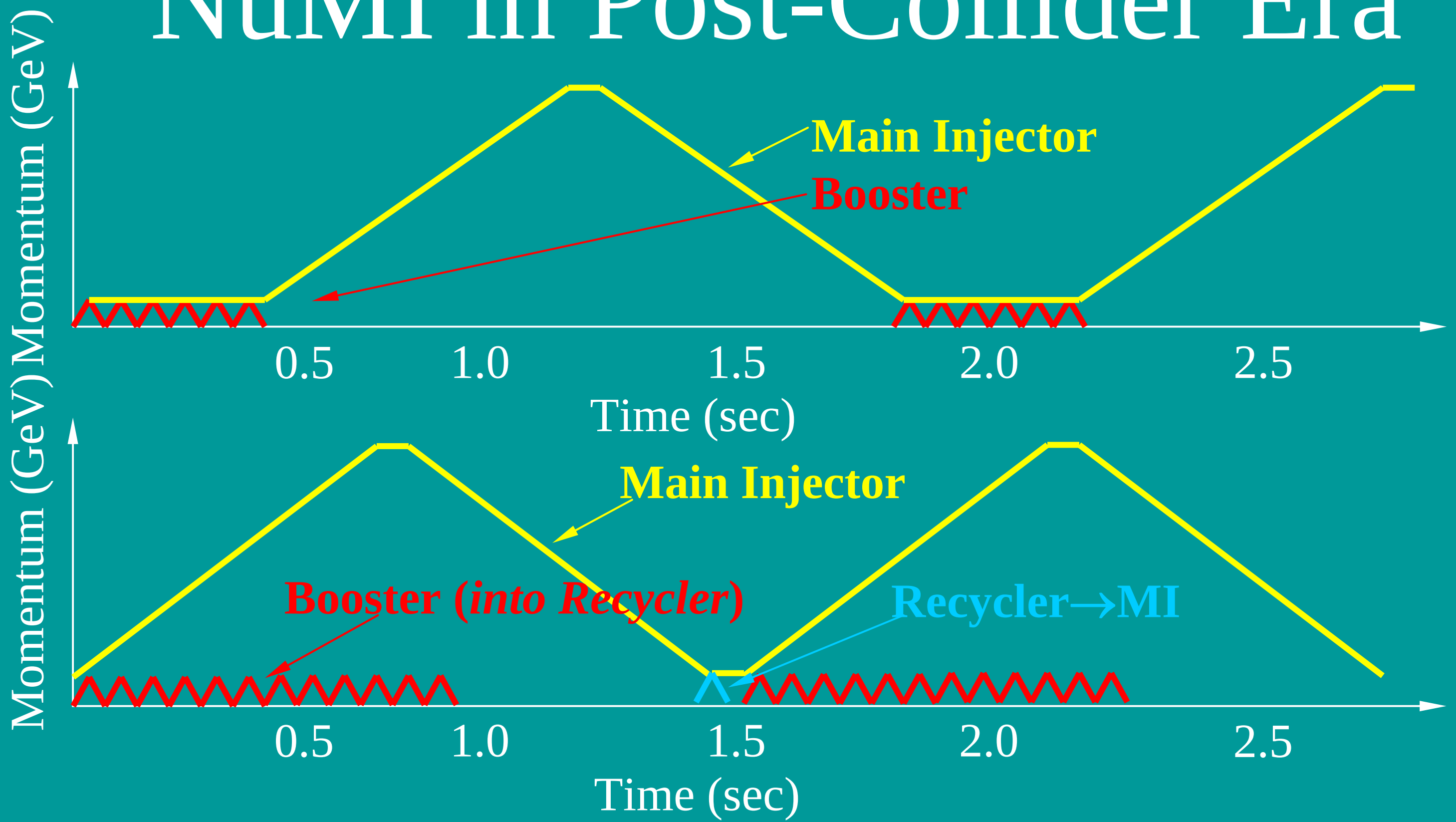
- "Conventional" ν beams require copious production of pions: $\pi^+ \rightarrow \mu^+ \nu_\mu$ (*or* $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$)
- These are created by collisions in a target, then a drift region for the pions to decay.
- NuMI beam aimed at Soudan Underground Laboratory (Minn, USA), also off-axis beams to sites in Minn, Canada

NuMI in the Collider Era

- MI ramp time ~1.5sec
- MI is fed 1.56μs batches from 8 GeV Booster
- Simultaneous acceleration & dual extraction of protons for
  - Production of $\overline{p}$ (Tevatron collider)
  - Production of neutrinos (NuMI)
- NuMI designed for
  - 8.67 μs single turn extraction
  - 2-3×10^{13}ppp @ 120 GeV
- Current limitations:
  - Booster can deliver at most 5×10^{12}p/batch
  - Gymnastics associated with mixed Pbar/NuMI operations



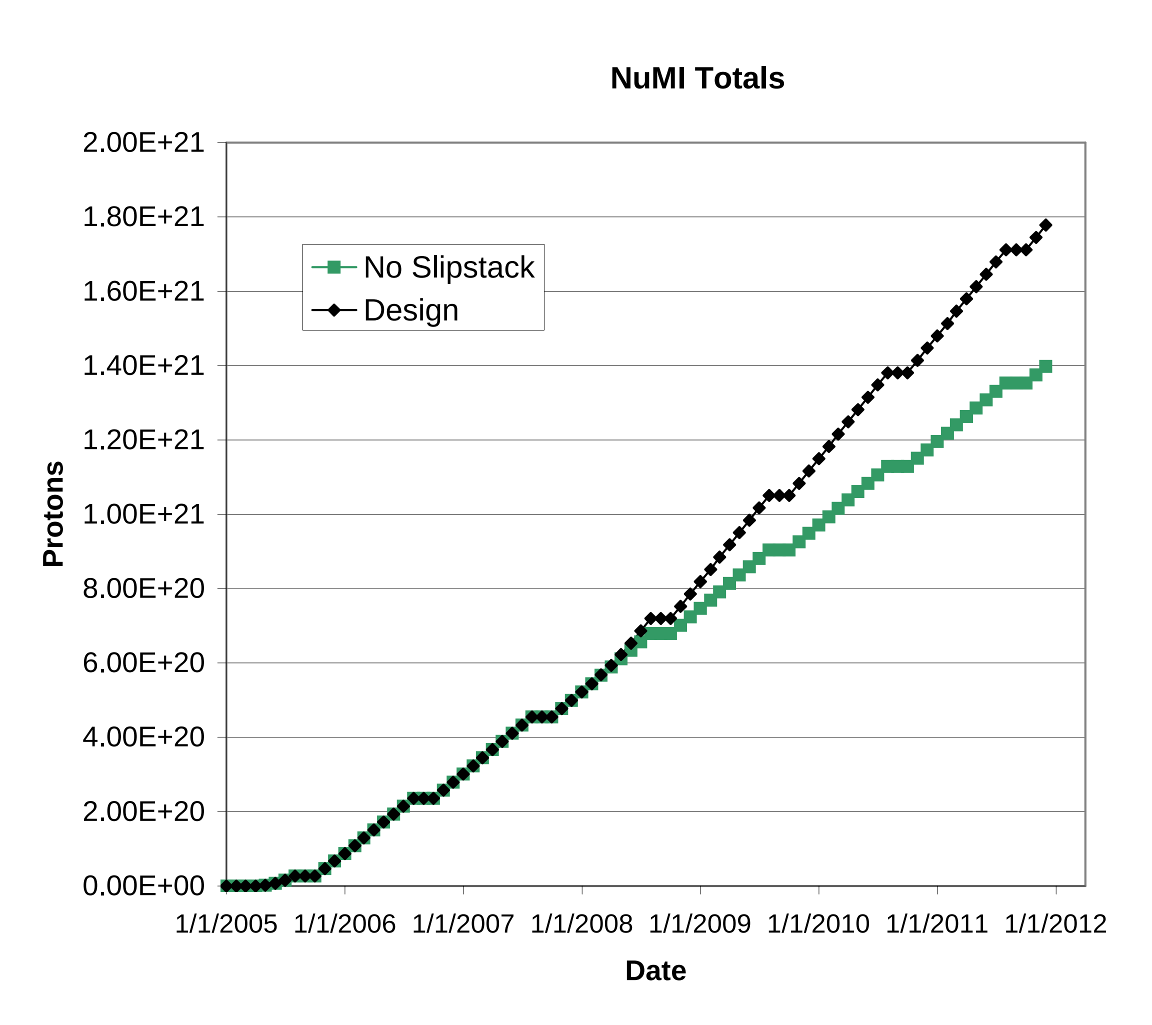
NuMI in Post-Collider Era

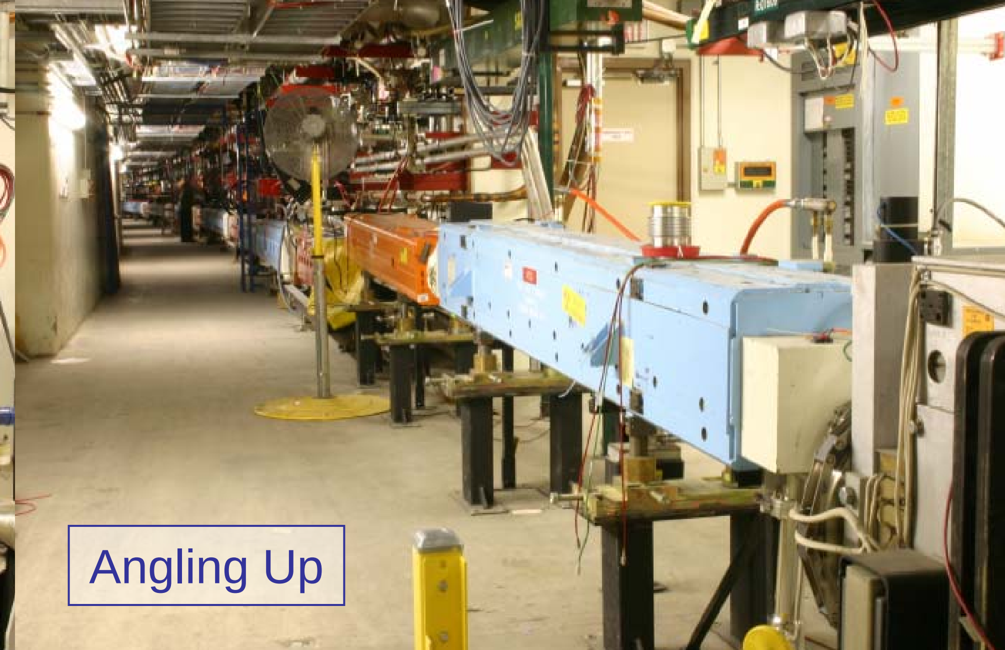


- The "Proton Plan" is an upgrade strategy already underway at FNAL
  - Component upgrades to Booster to enable 7.5Hz operation
  - Larger aperture quads, commissioning of 'slip-stacking' of Booster batches for NuMI
- New plan:
  - Inject 6-12 Booster batches into Recycler (takes 372-755msec)
  - Option: perform batch stacking in Recycler (12batches merged into 6)
  - Fast transfer of 8 GeV protons into MI for acceleration to 120 GeV.
  - Our existing 250kW proton beam becomes 330kW (480kW if stacking works)

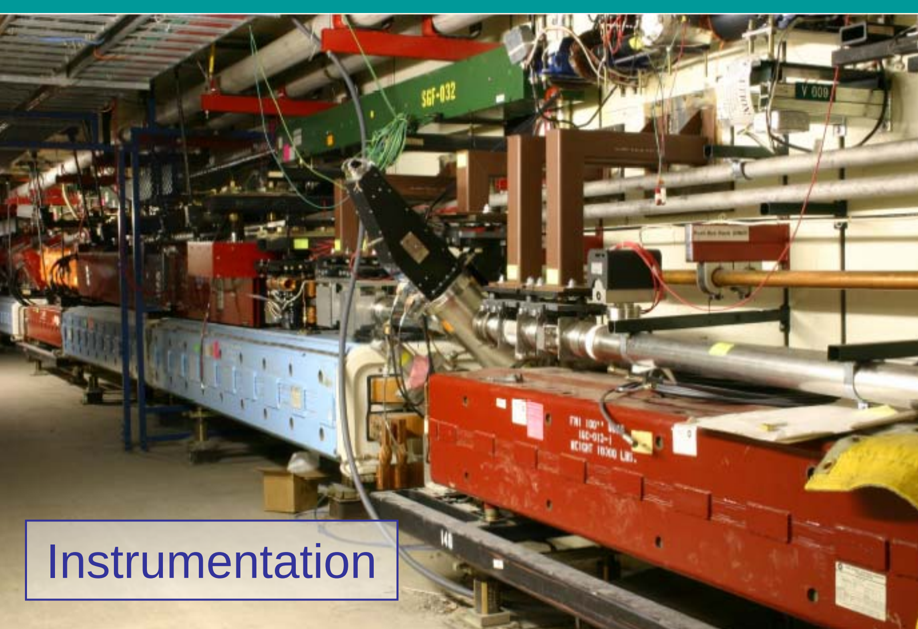
Beam Projections

- Present proton source is working on 2.5E20 POT / yr
- Commissioning of stacking and Recycler loading readily allows for 6-7E20 POT/yr
- At this level the required upgrades to are not yet substantial (~$1M)





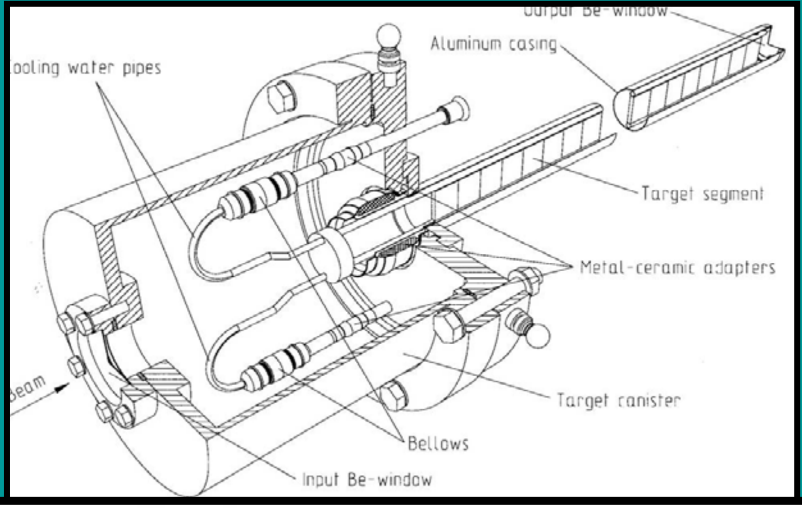
NuMI in Main Injector Tunnel

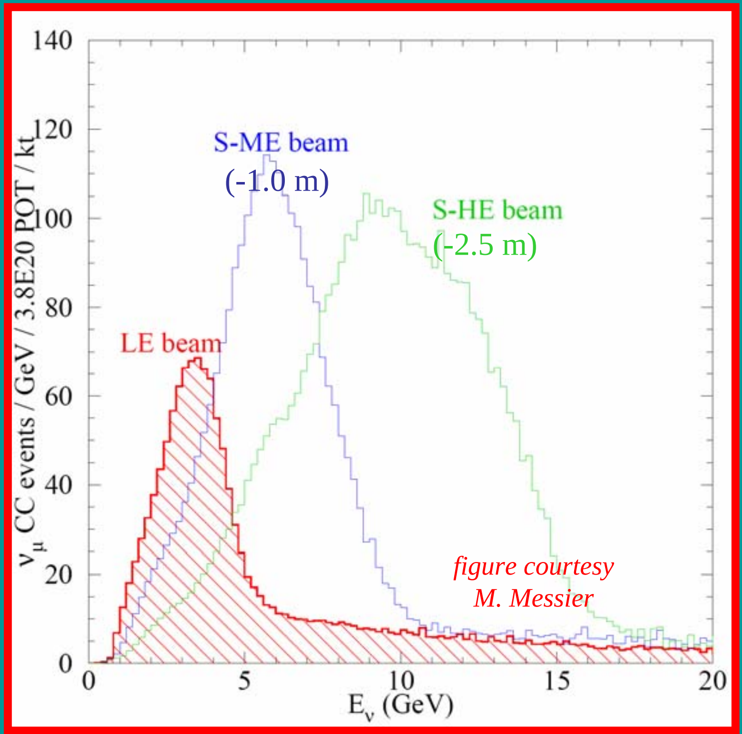


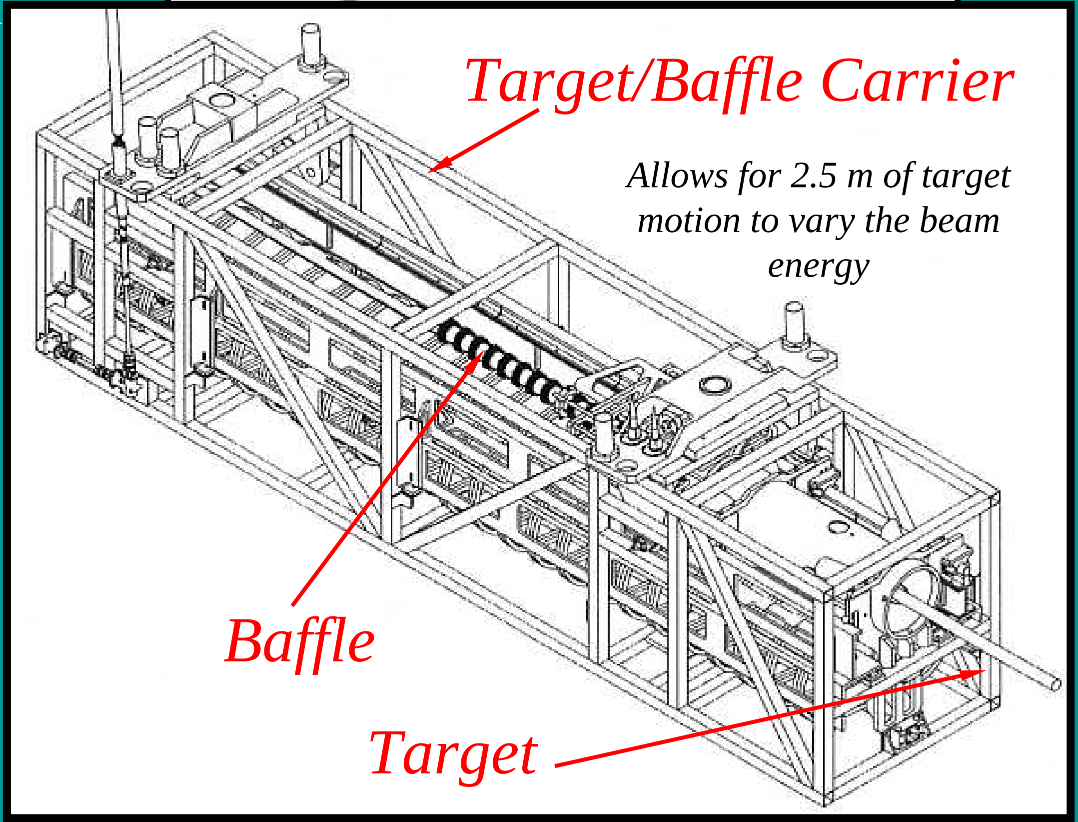
Extracted Proton Beam Line

NuMI Target

- 47 × 2 cm graphite segments
  - 6.4 × 15 mm^2 profile 1.9 interaction lengths
- Water cooled
  - 4 kW deposited beam power
  - Could survive 1MW proton beam if spot size increased to ~2mm







Focusing Horns

Horn 2 suspended from shielding module being lowered into shielding pit

Main horn field between conductors

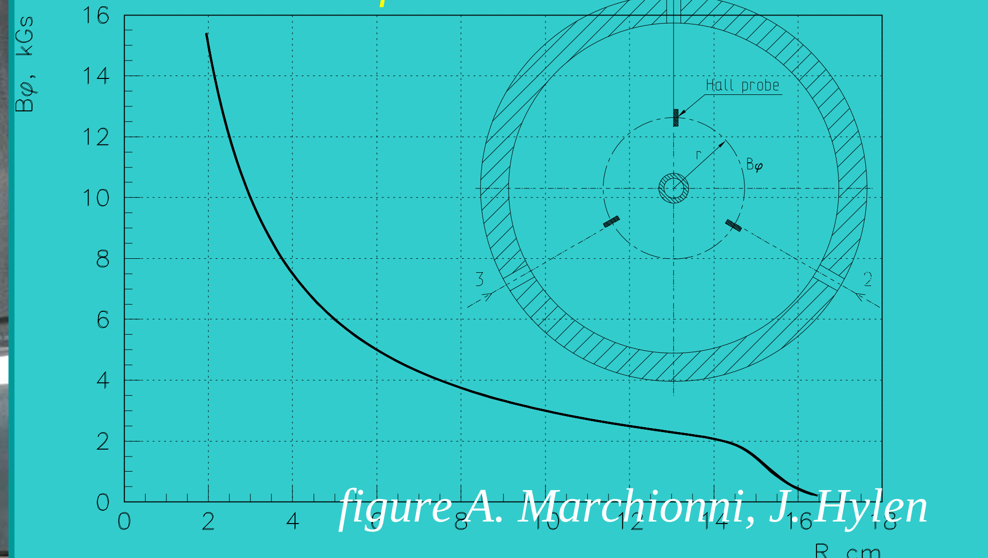
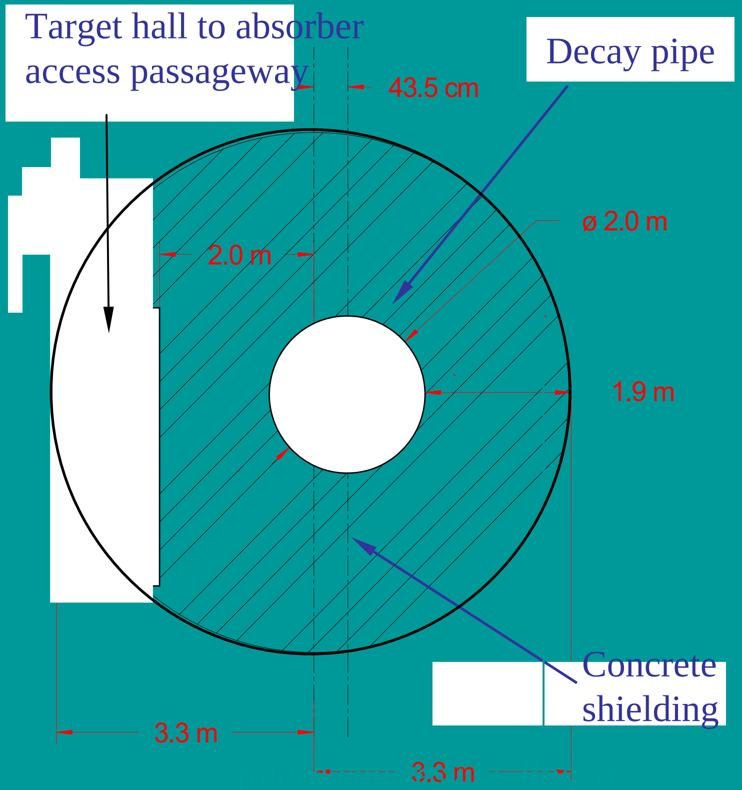


figure A. Marchionni, J. Hylen

Hall probe moving along horn axis

Decay Volume

- Bored tunnel back-filled with concrete
- Decay region power deposition
  - 63 kW in steel decay pipe
  - 52 kW in shielding concrete
  - Peak power in the steel ~360 W/m
- May be expensive to upgrade for >1 MW beam intensity.



Beam Absorber

- Absorber core
  - 8 aluminum plates
    30.5 x 129.5 x 129.5 cm^3
  - dual water-cooling paths
    8 kW peak power in one module
    (normal beam conditions)
  - followed by 10 plates of steel, each 23.2 cm thick.
- Total power into Absorber: 60 kW

  (400 kW beam power if accident)
- Water-cooled Aluminum easily can accommodate increased beam power from proton source upgrade
- Steel is more problematic – require adding water cooling?

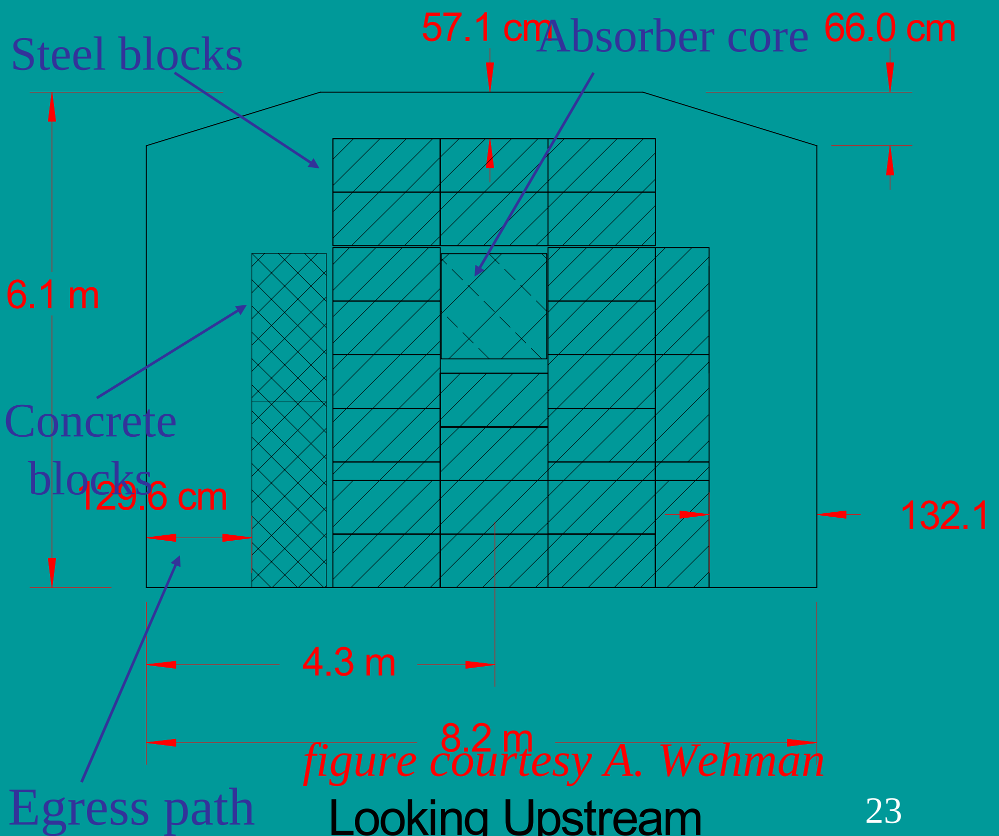


figure courtesy A. Wehman

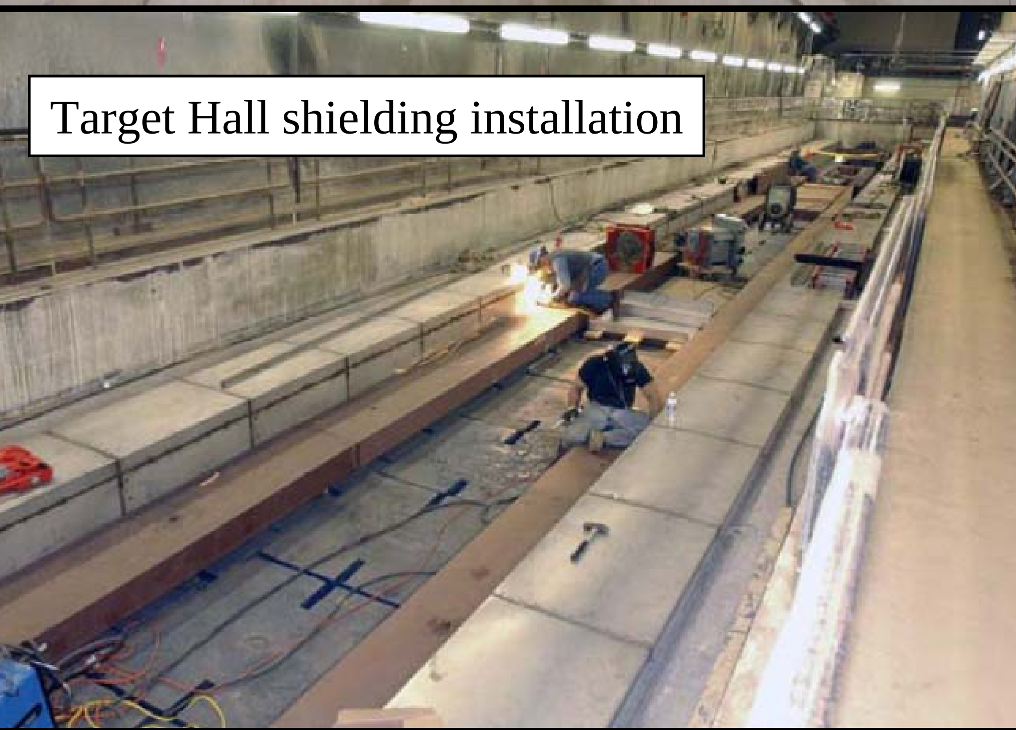
Summary

- NOvA has “Stage I” approval from FNAL PAC this past April 2005 meeting.
- R&D funds being allocated to optimize detector geometry, building
- FNAL will seek CD-0 status for NOvA
- NuMI beam line is fully up and running.
- Main Injector being tuned to handle RunII+NUMI

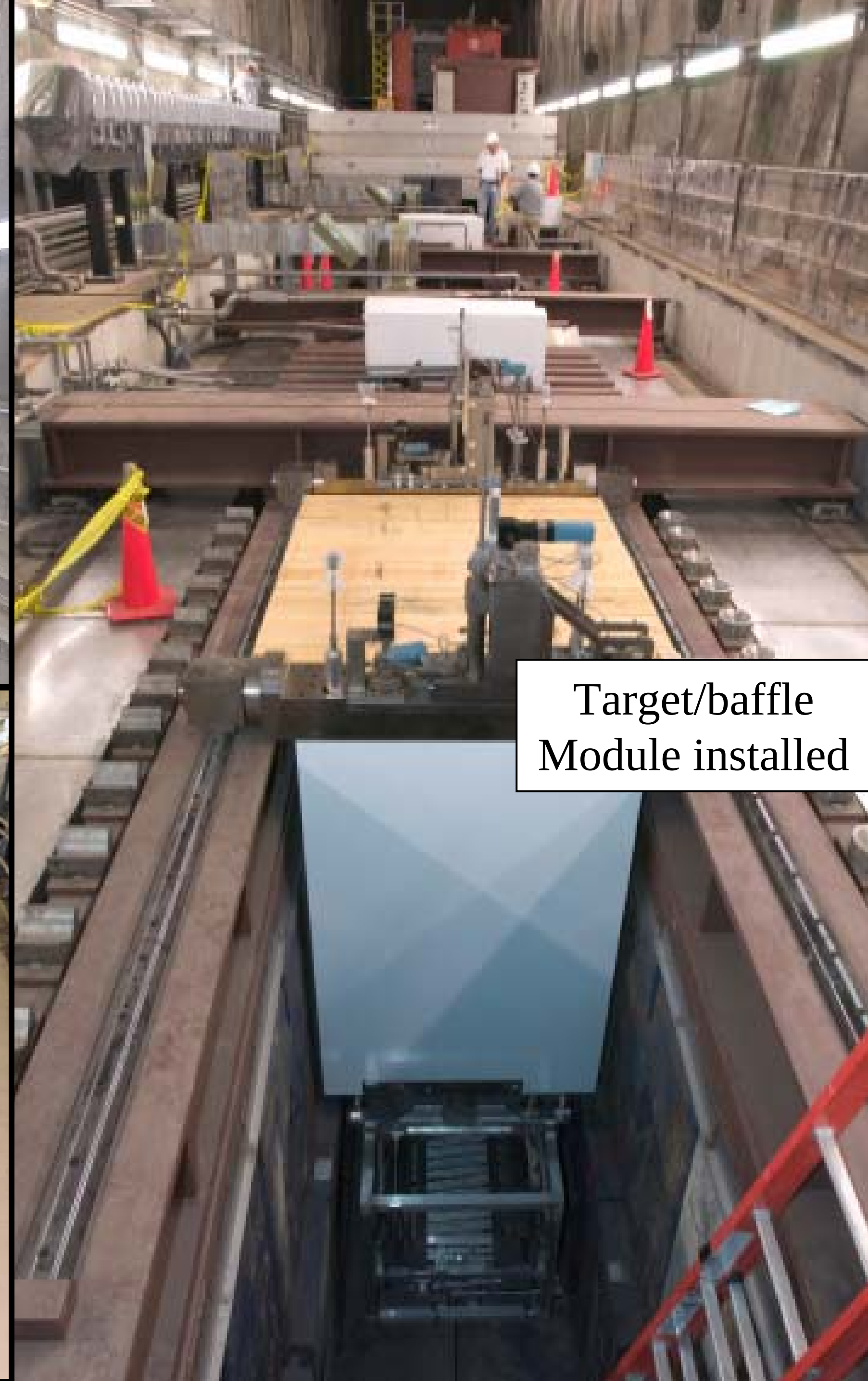
- 1st test combined MI operation for NuMI and *p* production 3/8/05-3/23/05.
- Operations resumed in April following repair of leak in target.
- Thus far ~ 2×10^{18} protons on target (presently ~ 2×10^{17} POT/day). Last night got $1.7\text{x}10^{13}$ / 2 sec for a few hours - nominal is $2.5\text{x}10^{13}$ / 2 sec.
- Have achieved 80kW beam power on target
(MI goal for 2005: 250kW, NuMI design capacity 400kW)
- Neutrinos observed in MINOS detector in Soudan, MN.

Target Hall

Target Hall after Contractor completion



Target Hall shielding installation



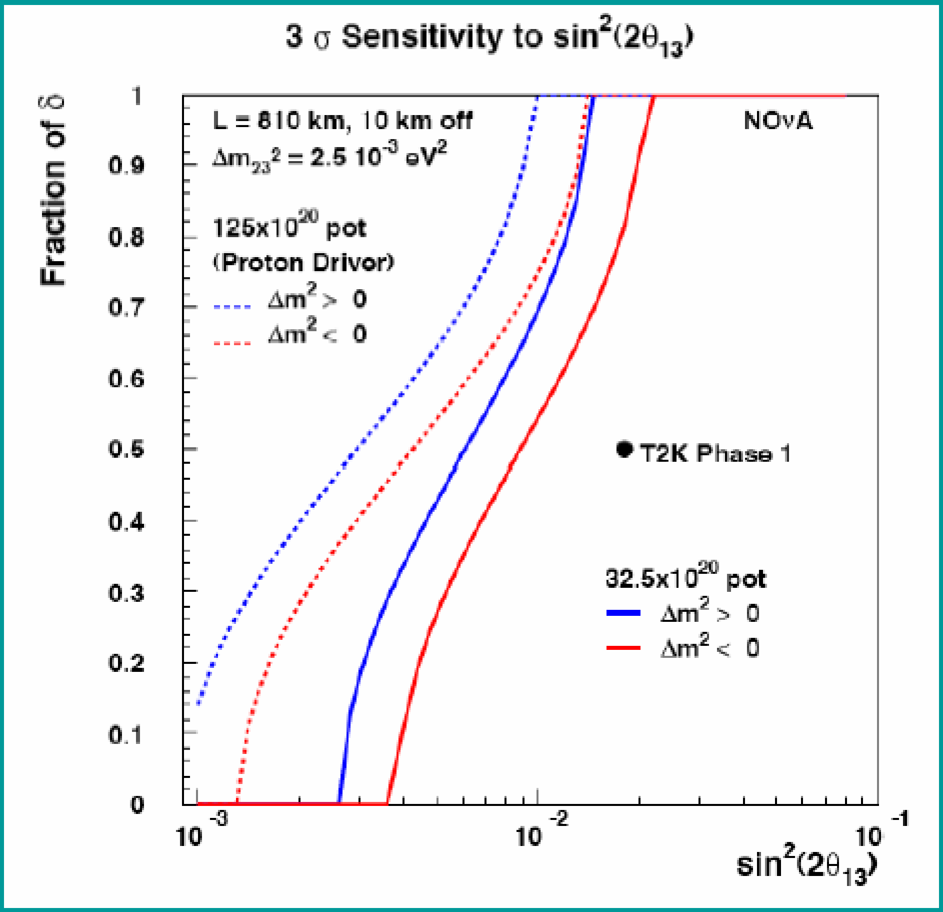
Target/baffle Module installed

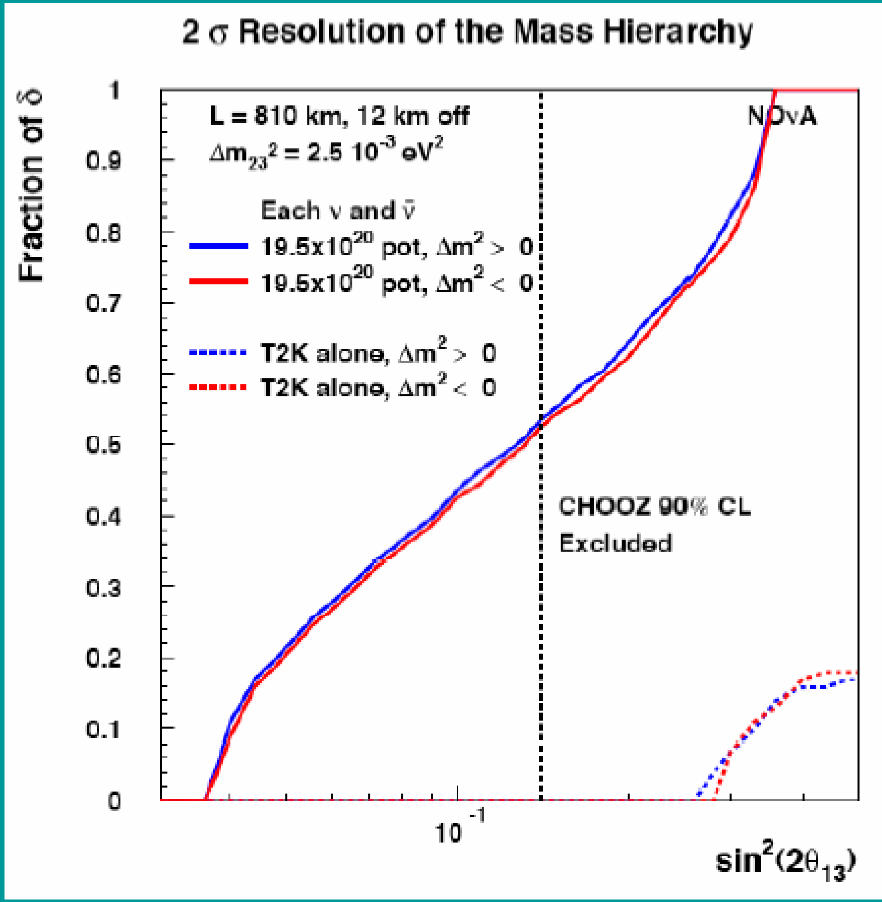
Summary of NuMI Upgradeability

Item	4E13 ppp (1.9sec rep)	8E13 ppp (1.9sec rep)	1.5 E14 ppp (1.9sec rep)
Radiation Issues	OK	seal chase more ($250K)	seal chase more ($500K)
Collimators	may need	very likely need (3@ $60K= $180K)	very likely need (3@ $60K= $180K)
Primary Beam and Power Supplies	OK	OK	OK
Target and Target Cooling	OK	OK	New Target and Cooling ($750K)
Horns and Cooling	OK	OK	OK
Target Chase Cooling and Shielding	OK	**cooling for stripline? ($500K)**	**Cooling for whole chase ($5 million)**
Hadron Absorber Cooling	OK	probably OK	Additional cooling needed ($1 million)
Decay pipe cooling	OK	**don't know**	**need cooling ($1 million??)**
Additional Cooling ponds	may need more	may need ($150K)	will need ($400k)
Total		$ 1 million +??	$9 million

table courtesy N. Grossman

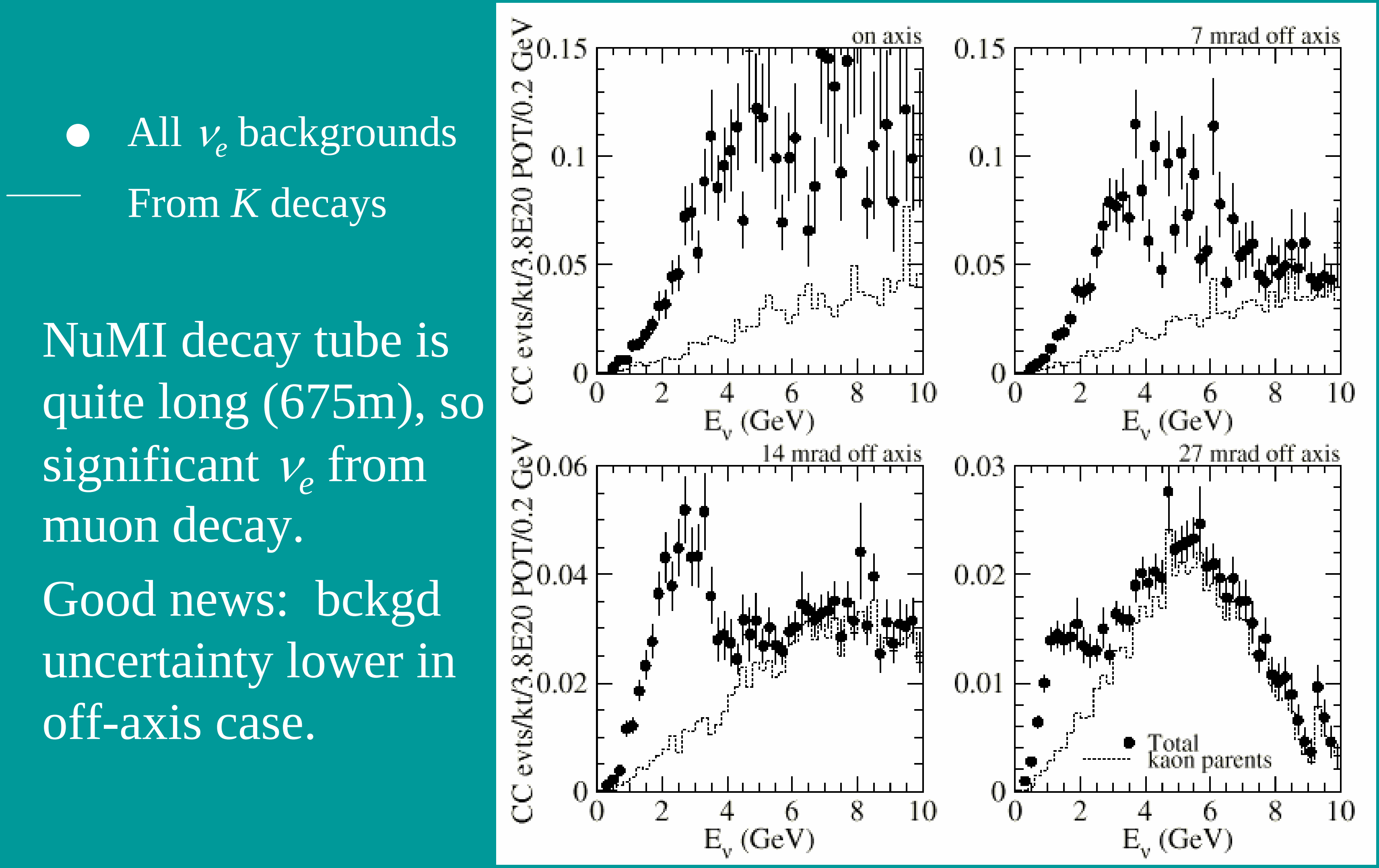
What Does NOνA Add to T2K?





- For now let us just look at T2K Phase I and NOνA prior to proton driver upgrades at FNAL since these may be a ways off.

Instrinsic ν_e in Off-axis Beam



- NuMI decay tube is quite long (675m), so significant ν_e from muon decay.
- Good news: bckgd uncertainty lower in off-axis case.